

**MODELLING DUST HALOS
IN COMET HALE-BOPP (C/1995 O1)
AND EVIDENCE FOR TWO ACTIVE NUCLEI**

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Modelling Dust Halos in Comet Hale-Bopp (C/1995 O1) and Evidence for Two Active Nuclei

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Abstract. Morphology of the comet's expanding, nearly-concentric dust halos extensively observed in February–April 1997 is modelled by employing a Monte Carlo computer simulation technique. A satisfactory model for the halos in late March requires only a slight correction to the spin-vector position determined previously from the diurnal evolution of a jet on Feb. 28. A surprising result is the finding that, with this spin constraint, the halos observed only a few days before the jet cannot be accounted for by ejecta from any combination of dust sources on the nucleus. Instead, the presence of a source on another nearby object – a second nucleus – is unequivocally implied. The spin vectors of the two nuclei are found to have subtended an angle $>90^\circ$, in spite of practically the same tilt of their equatorial planes to the comet's heliocentric orbital plane. Dust emission from the second nucleus is also shown to account for some fine jet features observed in late March. It is recalled that the existence of a massive satellite was reported elsewhere, based on independent evidence.

Key words: comet Hale-Bopp – dust-halo morphology – computer image simulation – dust from a comet pair

1. Introduction

Extensive monitoring of dust jets and other features displayed by comet Hale-Bopp in early 1997 (e.g., Lecacheux et al. 1997; Jorda et al. 1997; Sarmecanic et al. 1997a, b; Kidger 1997; Farnham et al. 1998; Licandro et al. 1998) led to a number of independent rotation-period determinations, all clustering near $11^{\text{h}}20^{\text{m}}$. Most of these studies found that the period did not detectably vary with time.

From his comprehensive modelling of the diurnal evolution of a jet on 1997 Feb. 28, Sekanina (1998a) was able to derive an accurate position of the comet's north rotation pole, described by R.A. = 257° , Decl. = -61° (eq. J2000.0) and implying the axial tilt of 75° . He found that

the dust source was located at a cometocentric latitude of $+55^\circ$ (the unknown nuclear shape being approximated by a sphere) and that, after several rotations, the jets could turn into a system of halos in the southwestern quadrant. The derived polar coordinates are fairly consistent with those reported by Sera-Ricart et al. (1998) and are used in Sec. 4 to define a “reference” spin-vector orientation.

2. Dust Halos

The formation of nearly-concentric, expanding dust halos is well understood (Sekanina and Larson 1984; Sekanina 1987): they are identified with the relatively sharp outer boundaries of the conical sheets of particulate ejecta from a discrete source on the sunlit side of a *rapidly* rotating cometary nucleus, and accompanied by constraints on the comet-Sun-Earth configuration. The halos are dominated by submicron-sized grains whose ejection velocities are nearly independent, within a range, of grain size; the expansion rate is determined by the peak particle velocities.

In comet Hale-Bopp, multiple halos (also called ripples, shells, rings, waves, arcs, hoods, etc.) were first described by Hergenrother et al. (1997) on images taken on 1997 Feb. 1. The halos were observed extensively during February–April 1997. Some of the most spectacular halo structures are seen on the computer-processed images of the CCD frames taken by J. A. DeYoung with the U. S. Naval Observatory's 61-cm f/13.5 reflector and the Kron-Cousins I filter. Two images, from 1997 Feb. 23.44 UTC and March 25.01 UTC, are shown in Fig. 1.

3. Pure Spin Approximation to the Rotation State

From available information, comet Hale-Bopp's rotation can be approximated by pure spin on several time scales. Since Sekanina's (1998a) successful model for the jet's diurnal variations was built on this premise, it follows that pure spin is adequate on time scales of at least ~ 0.5 day.

The fact that up to at least seven nearly-concentric halos are apparent on some images (see Fig. 1) implies that pure spin is acceptable on time scales of >3 days.

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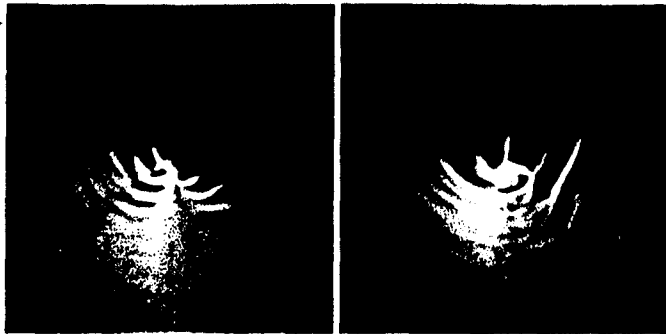


Fig. 1. Computer-processed images of the systems of dust halos in comet Hale-Bopp detected on 1997 Feb. 23.44 UTC (left) and March 25.01 UTC (right). The observations were made by J. A. DeYoung with the U.S. Naval Observatory's 61-cm f/13.5 reflector through the Kron-Cousins I filter. The scale was 0.48 arcsec per pixel. The co-added images consisted of 89 motion corrected exposures, each of 5-second duration (total integration of 7.4 minutes) on Feb. 23 and 150 2-second exposures (total integration of 5 minutes) on March 25. Computer processing of these frames, due also to DeYoung, involved application of the adaptive-histogram-equalization technique (AHEQ), written by R. E. Schmidt and L. Gritz. Either of the two images is 4 arcmin on a side. North is up, east to the left.

Finally, from Farnham et al.'s (1998) accurate determination of the rotation period based on images between 1997 March 25 and April 1 it follows that pure spin still satisfactorily approximates the comet's state of rotation on time scales as long as one week. Indeed, if pure spin were unacceptable, the halos could not appear as simple arcs and Farnham et al. would have failed in their efforts.

Over longer time spans the situation is more uncertain. For example, Sekanina and Boehnhardt (1998) presented two models for the comet's porcupine-like appearance in 1996: one with an inertially fixed rotation axis, the other with a wobbling axis. From their models of dust features in September 1996–May 1997, Vasundhara et al. (1998) and Metchev and Luu (1998) independently described the comet's long-term rotational motion as complex.

4. Monte Carlo Simulation of a System of Halos: Evidence for Contributions from Two Objects

The objective of this investigation is to model morphology of the dust halos that appear on the digitally-processed images displayed in Fig. 1. The employed Monte Carlo computer-simulation technique generates synthetic images of dust ejecta released from discrete sources on a rotating nucleus. The dust sources are assumed to be active only when located on the sunlit side of the nucleus, in conformity with the conclusions by Keller et al. (1987) on dust emission from the nucleus of Halley's comet. The models are characterized by their rotation constants and by the dust-source and dust-ejecta parameters, which are derived by a trial-and-error fit to the observations. Brief de-

scriptions of the image-simulation technique can be found elsewhere (Sekanina 1996a, b, and references therein).

To model morphology, no photometric information is necessary, so that the dust-ejecta parameters may not be tightly constrained. Their values adopted here are generally similar to those employed in modelling the jet's evolution (Sekanina 1998a). Digital scatter has been introduced in the synthetic images to mimic observational noise.

The first step in modelling the systems of halos on the images in Fig. 1 is to compare their morphology with that of the dust coma on a sequence of "standard" synthetic images, computed with the reference spin-vector constants (Sec. 1) and with the location of a dust source on the nuclear surface varying stepwise in cometocentric latitude. The purpose of this exercise is to find out whether the basic features of the observed halos can be reproduced by dust ejecta patterns from any location on the sunlit side of the nucleus. The condition of constant dust production between sunrise and sunset has in this phase been retained, with the comet's activity profile assumed to remain unchanged over a period of at least seven rotations immediately preceding the observation, at which time the dust source has been assumed to transit the antisolar meridian. This last constraint does not affect the overall morphology of the models, except for a slight phase shift in the halo spacing and some effects very close to the nucleus.

For reasons that will become obvious shortly, the results of modelling the halo system on 1997 March 25 are presented first. For the reference spin-vector orientation, the nuclear surface that on this date was sunlit at least briefly during rotation was the entire area to the north of latitude -26° . The calculated dust-emission patterns from discrete sources situated between the latitudes of -15° and $+85^\circ$ and spaced at 10° intervals are compared with the observed halo morphology in Fig. 2. Its inspection reveals unequivocally that the simulated patterns for the low northern latitudes, near $+15^\circ$, match the observed appearance fairly satisfactorily. An obvious conclusion, to be further examined and refined in Sec. 5, is that a slight adjustment to the reference spin-vector position should make the fit to the observed features quite acceptable.

If this reference spin-vector position for an epoch of 1997 Feb. 28 represents a fair approximation to the rotation state of the nucleus at an epoch some four weeks later, one would expect that it should be most appropriate for modelling a system of halos observed within a few days of the jet. This expectation is also supported by Farnham et al.'s (1998) successful analysis. Since on 1997 Feb. 23 the nucleus could be sunlit as far south as the latitude of -62° , the models for dust emissions from isolated sources located between the latitudes of -45° and $+85^\circ$ are provided for comparison with the observed features in Fig. 3. The result of this exercise is startling: *the entire system of halos in the southeastern quadrant could not be matched by dust ejecta from sources at any location of the nucleus*. Since the basic halo morphology varied insignificantly from day

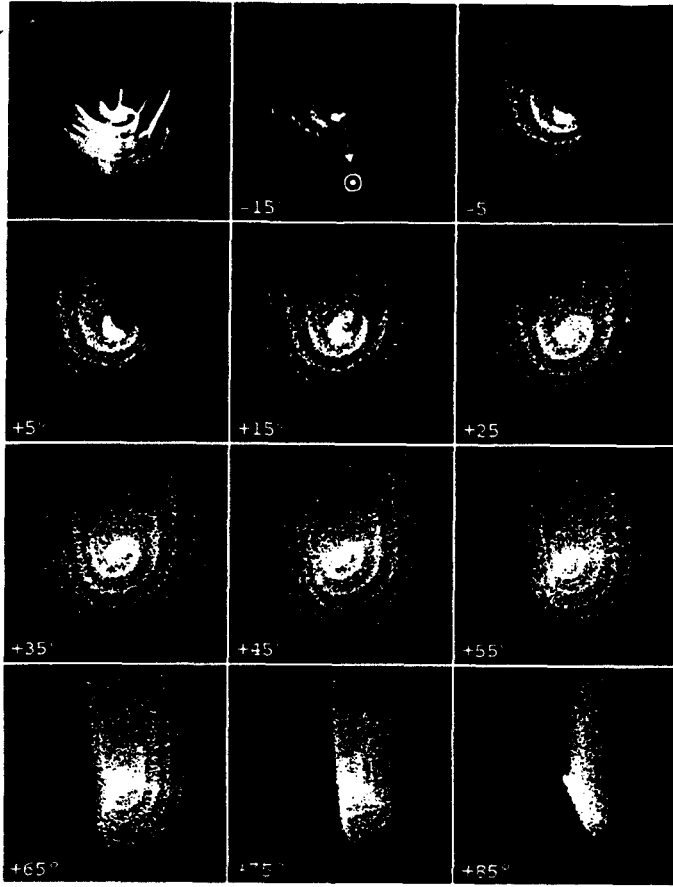


Fig. 2. Comparison of DeYoung's computer-processed image of comet Hale-Bopp on 1997 March 25.01 UTC from Fig. 1 with a set of computer-generated images, based on the reference spin-vector orientation (R.A. = 257° , Decl. = -61°). The sources, with a constant dust production rate between sunrise and sunset, are at latitudes -15° to $+85^\circ$, as indicated. The Sun's direction (\odot) is depicted in the first synthetic image. Each frame is 4 arcmin on a side. North is up, east to the left.

to day, this result is insensitive to the choice of date in the time span from late February to early March 1997.

This major conclusion has far-reaching implications. The point to be addressed next is: Could the southeastern branch of halos be matched at all? And if so, under what conditions? Experimentation with the model parameters shows the need for only a minor (if any) correction to the tilt of the rotation axis relative to the orbital plane, but for a considerable, more than 90° , shift in the axial orientation relative to the reference spin-vector position. Since one cannot accommodate this major change in the rotation and simultaneously account for the very orderly recurring halos, the only possible solution is to admit that the observed features are *products of dust emission from two nearby objects: the nucleus and its companion*.

It is recalled that the existence of a massive satellite to the primary nucleus was deduced from entirely independent evidence elsewhere (Sekanina 1998b).

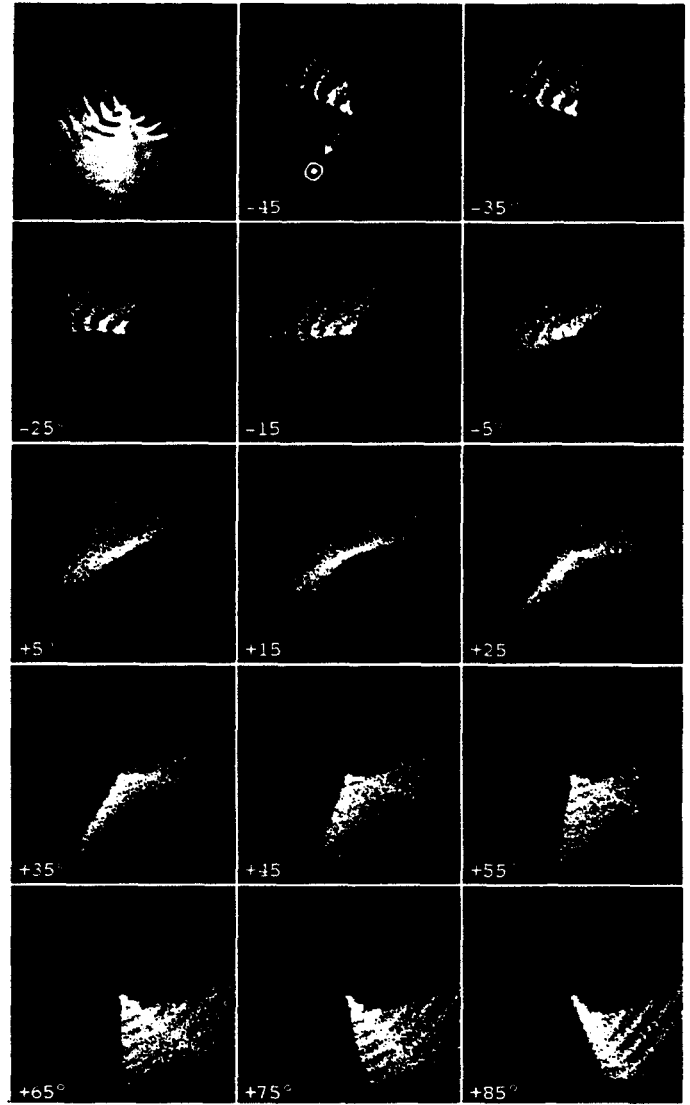


Fig. 3. Comparison of DeYoung's computer-processed image of comet Hale-Bopp on 1997 Feb. 23.44 UTC from Fig. 1 with a set of computer-generated images, based on the reference spin-vector orientation (R.A. = 257° , Decl. = -61°). The sources are at latitudes -45° to $+85^\circ$, as indicated. For information on the source emission profile, the Sun's direction, and the frame size and orientation, consult the caption to Fig. 2.

5. Monte Carlo Simulation of a System of Halos: The Refined Model and Conclusions

In practice, one cannot unequivocally determine which of the halos come from the primary nucleus and which from the companion. The object, whose north rotation pole pointed at R.A. = 257° , Decl. = -61° in late February 1997, will be called nucleus A. By late March this position moved to R.A. = 262° , Decl. = -72° . The rotation axis of the other object, nucleus B, is less well constrained. The position of its north rotation pole is estimated at R.A. $\simeq 115^\circ$, Decl. $\simeq -10^\circ$ in late February and

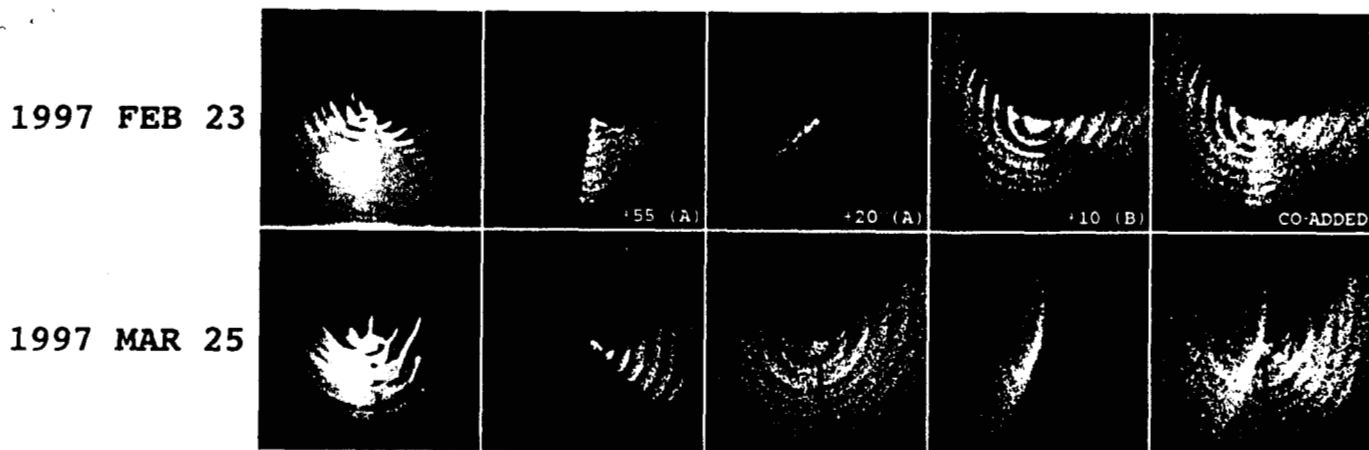


Fig. 4. Models for halos in comet Hale-Bopp on 1997 Feb. 23 and March 25. From left to right: DeYoung's computer-processed image; the computer-generated images for, respectively, two sources on nucleus A, at latitudes $+55^\circ$ and $+20^\circ$, and one source on nucleus B, at latitude $+10^\circ$, as indicated; and the final model image, obtained by co-adding the three synthetic images. The condition of constant diurnal dust production has been relaxed. Each frame is 4 arcmin on a side. North is up, east to the left.

at R.A. $\simeq 115^\circ$, Decl. $\simeq 0^\circ$ in late March. The tilt of the equatorial plane to the comet's heliocentric orbital plane was 75° for nucleus A in late February and for nucleus B at both epochs, and 80° for nucleus A in late March. Both nuclei are assumed to spin with a period of $11^{\text{h}}20^{\text{m}}$. The primary nucleus may be either of the two objects. The polar position of nucleus B is similar to that derived from one of the three 1995 dust emission events (Sekanina 1996a).

The model proposed for the halos, by no means unique, is shown in Fig. 4. The condition of constant dust production has been relaxed. The resulting synthetic images consist of contributions from three sources: two on nucleus A and one on nucleus B. The sources on nucleus A were at latitudes $+55^\circ$ (the jet's source; cf. Sekanina 1998a) and $+20^\circ$. The latter source, not very active in late February, was trailing by $\sim 90^\circ$ in longitude. The source on nucleus B was at latitude $+10^\circ$. The match between observation and model is acceptable. Besides the halos, the fitted features include some jets on both dates and a system of parallel crossbars, which seem to connect some of the halos in the southwestern quadrant in March due to projected superposition of the ejecta from the two sources on nucleus A. Work on dust morphology of this comet is continuing.

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